SHAPED ANODE X-RAY TUBE

The present application relates to the x-ray tube arts. The invention finds particular application in x-ray tube assemblies for large bore computed tomography scanners. It is to be appreciated, that the present invention finds further application in other higher power x-ray devices where it is desirable to increase the anode current without incurring a heat loading which is damaging to the anode.

Computed tomography (CT) scanners radiographically examine a subject disposed on a patient support and generate diagnostic images of the subject. An x-ray tube assembly is mounted on a rotating gantry and projects a beam of radiation through a section of the subject which is detected by a detection system, such as an array of two-dimensional detectors which are mounted on the rotating gantry or a ring of detectors on the stationary gantry. To increase the width of the slice or cone beam which is irradiated, the width of the detector array, parallel to the axis of rotation of the anode, has been progressively increased. This increased width, in combination with faster scan times, places higher demands on the x-ray tube, in terms of generating a higher x-ray flux.

X-rays from conventional rotating anode x-ray tubes are typically emitted from a target on the sloped, peripheral edge of the anode typically at a point nearest the patient, where the electrons strike and are converted to x-rays. The x-ray beam is typically collimated into a fan or wedge of x-rays at an angle which is about 90° to the beam of electrons striking the anode. The peripheral edge is generally provided with a slope to increase the target area at which a focused election beam strikes the anode, thereby decreasing the current loading per unit area of the target. The width of the x-ray beam source (the focal spot width) is a projection of the height (radially) of the target area. More

specifically, the projection is a function of the electron beam height times the tangent of the angle of the slope of the peripheral face of the anode.

As a result of the demand for higher loadings, in recent years, the slope has decreased from about 10° (relative to an axis perpendicular to the beam of electrons) to about 7°, or less. As seen from the table below, this enables an increase of over 40% in anode current for the same heat loading at a given projected focal spot size as viewed in the x-ray beam direction.

Anode slope (degrees)	Slope length (mm) for a 1 mm projection	Relative loading
6	9.51	168
7	8.14	144
8	7.12	125
9	6.31	111
10	5.67	100
11	5.14	91
12	4.70	83

At shallow angles (e.g., 7°), however, there is a tendency for the x-ray beam to be truncated or reduced in x-ray flux at the heel. Specifically, not all the incident electrons generate x-rays at the surface of the anode face. Rather, some electrons penetrate deeply within the target before generating x-rays. X-rays generated at the surface do not pass through the anode, provided the beam angle is not wider than twice the target slope. However, x-rays generated within the target must pass through it and are attenuated by the heavy metal of the target. The flatter the slope of the peripheral face and the wider the beam angle, the further the interior-generated x-rays must travel through the anode metal before emerging in the direction of the output beam. The heel effect attenuation is greater for x-rays on the anode side of the beam.

The CT scanner manufacturer is thus faced with the choice of specifying either an anode of shallow slope (e.g., 7°), which is limited in terms of the beam angle it can provide because of the heel effect, or of steeper slope (e.g., 10°), which is limited in terms of the loading it can sustain.

The present invention provides a new and improved method and apparatus which overcome the above-referenced problems and others.

In accordance with one aspect of the present invention, an x-ray tube is provided. The x-ray tube includes an envelope which defines an evacuated chamber and a source of electrons. An anode is mounted in the chamber for rotation about an axis of rotation. The anode defines a sloped peripheral region on which a target area is defined, which target area is struck by electrons emitted by the electron source and emits x-rays. The sloped peripheral region includes a first annular portion sloped at a first angle relative to a plane perpendicular to the axis of rotation and a second annular portion, adjacent the first, sloped at a second angle relative to the plane. The second angle is different from the first angle. The target area is defined partially on the first annular portion and partially on the second annular portion.

In accordance with another aspect of the present invention, a method of generating a beam of x-rays is provided. A beam of electrons is accelerated and focused to strike a target area on a sloping peripheral region of an anode which rotates about an axis of rotation. The anode peripheral region includes a first annular portion sloped at a first angle relative to a plane perpendicular to the axis of rotation and a second annular portion radially spaced from the first and sloped at a second angle. The second angle is different from the first. The target area is defined

partially on the first annular portion and partially on the second.

One advantage is that it enables an anode to have a shallow slope while maintaining a sufficiently large beam angle.

Another advantage of at least one embodiment of the present invention is that it facilitates generating higher flux, wider x-ray beams.

Another advantage resides in reduced anode heating.

Still further advantages of the present invention will become apparent to those of ordinary skill in the art upon reading and understanding the following detailed description of the preferred embodiments.

The invention may take form in various components and arrangements of components, and in various steps and arrangements of steps. The drawings are only for purposes of illustrating a preferred embodiment and are not to be construed as limiting the invention.

FIGURE 1 is a diagrammatic illustration of a computed tomography scanner incorporating the present invention;

FIGURE 2 is a partial cross-sectional view of one embodiment of an x-ray tube of the computed tomography scanner of FIGURE 1;

FIGURE 3 is a detailed cross-sectional view of the anode of an x-ray tube of FIGURE 2;

FIGURE 4 is a diagrammatic cross-sectional view of an anode and filament combination of another embodiment;

FIGURE 5 is another diagrammatic view of a cross-section of anode and filament combination; and

FIGURE 6 is yet another diagrammatic, partial cross-sectional view of an anode and cathode filament combination.

With reference to **FIGURE 1**, a computed tomography (CT) scanner **10** radiographically examines and generates diagnostic images of a subject disposed on a patient support **12**. More specifically, a volume of interest of the subject on the support **12** is moved into an examination region **14**, typically by translating the support **12** in a direction **Z**. An x-ray tube assembly **16** mounted on a rotating gantry projects one or more beams of radiation through the examination region **14**. A collimator **18** collimates the beams of radiation in two dimensions. In the preferred embodiment, a two-dimensional x-ray detector **20** is disposed on the rotating gantry across the examination region **14** from the x-ray tube. In another embodiment, a ring or array of two-dimensional detectors is mounted on a stationary gantry around the rotating gantry.

The x-ray detector **20** operates in known ways to convert x-rays that have traversed the examination region **14** into electrical signals indicative of x-ray absorption between the x-ray tube **16** and the detector **20**. The electrical signals, along with information on the angular position of the rotating gantry, are communicated to a data memory **30**. The data from the data memory **30** is reconstructed by a reconstruction processor **32**. Various known reconstruction techniques are contemplated including cone beam, multi-slice, and spiral scanning and reconstruction techniques, and the like. The volumetric image representation generated by the reconstruction processor **32** is stored in a volumetric image memory **34**. A video processor **36** withdraws selective portions of the image memory to create slice images, projection images, surface renderings, and the like and reformats them for display on a monitor **38**, such as a CRT or LCD monitor.

With reference now to **FIGURE 2**, the x-ray tube assembly **16** includes a disk-shaped anode **40**, which is mounted within an air-evacuated envelope **42** and may be in a plane perpendicular to the axis of rotation of the rotating gantry, although other geometries are also contemplated. The evacuated envelope is surrounded with a lead or another high-

Z metal with good x-ray stopping power housing **44** which defines a cooling reservoir. A window **45** of beryllium or other low-Z metal or material defines an exit near the examination region **14** through which x-rays **46** enter the examination region **14**. Situated between the examination region **14** and the window **45** is a beam-shaping filter (not shown) and the collimator **18**.

The anode **40** has a sloped, annular peripheral edge **50** which is struck by a beam **52** of electrons generated by a source of electrons, such as a filament **54** of a cathode assembly. The beam of electrons is focused to strike a limited, defined area or target **56** on the sloped edge. The anode is mounted on a central shaft **58** and rotates about an axis **R**, which is generally parallel with the beam of electrons **52** and perpendicular to a front face of the anode. The sloped target **56** is spaced from the axis **R** by a distance $\mathbf{d_1}$ at its inner peripheral edge **60** and by a distance $\mathbf{d_2}$ at its outer peripheral edge **62**. The majority of the electrons in the beam **52** strike the anode in the target **56**, with only a minimal proportion striking other parts of the anode surface. The target **56** preferably receives at least 90% of the electrons which are emitted by the cathode and which hit the anode, more preferably, at least about 99% of these electrons.

The filament **54** is mounted in a cathode cup **70**, which acts as a focusing device to focus the electrons emitted by the filament into the beam **52** which is accelerated by a high voltage source **72** to the anode. The cathode cup and filament, which together make up a cathode assembly, remain stationary, with respect to the envelope **42**, although it is also contemplated that the cathode assembly may rotate while the anode remains stationary. In any event, the cathode assembly remains stationary with respect to the output beam **46**.

With continued reference to **FIGURE 2**, and reference also to **FIGURE 3**, the target **56** is defined partially on a primary portion **80** of the peripheral edge **50** and partially on

a secondary portion **82** of the peripheral edge. The secondary portion **82** is located radially inward of the primary portion **80**. The primary portion **80** extends at an angle **α** to a plane which is perpendicular to the axis **R** of the anode. The secondary portion extends at an angle **β** to an axis which is perpendicular to the axis **R** of the anode. Angle **β** is larger than angle **α**. In one embodiment, the angles **α** and **β** differ by at least 1°. In another embodiment, the angles differ by at least 2°. For example, angle **α** is from about 6° to about 8°, while angle **β** is from about 8° to about 12°. In one specific preferred embodiment, the angle **α** is about 7° and the angle **β** is at least about 9°, preferably 10°. The lower limit of the angle **α** depends on the detectors, the resolution, and the width of the beam desired. In currently available CT systems, these do not allow an angle **α** of much less than 6°, although it is contemplated that advances in CT scanner technology may permit smaller angles.

In the preferred embodiment, the majority of the electrons which strike the target **56** strike in the primary portion **80**. In one specific embodiment, at least about 60% of the electrons which strike the target, strike the primary portion **80**, with the balance of 40%, or less striking the secondary portion **82**. Preferably, at least 80% of the electrons striking the target **56** strike one or other of the primary and secondary portions, more preferably, at least 90%. In **FIGURE 3**, the primary portion **80** is shown as ending abruptly as the interface with the secondary portion **82**, although it preferably does not do so, as discussed below.

The combination of the primary portion **80** with the secondary portion **82** allows for a high power, due to the shallow angle of the primary portion, while reducing the heel effect with the secondary portion. The projection $\mathbf{p}_1$ of the x-ray beam from the primary portion **80** is related to the height $\mathbf{h}_1$ of the electron beam striking the primary portion by the expression:

$$p_1 = h_1 \quad \tan\alpha$$

and similarly for the secondary portion **82**:

$$p_2 = h_2 \quad tan\beta$$

where $\mathbf{p_2}$ and $\mathbf{h_2}$ are the projection and height, respectively, of the secondary portion. It will be appreciated that $\mathbf{h_1}$ and $\mathbf{h_2}$ may be less than or equal to the actual heights of the primary and secondary portions, where the electron beam width **w** does not extend beyond these portions. For this embodiment, where the first and second portions are directly adjacent, $h_1 + h_2 = h_T = w$.

With reference once more to **FIGURE 2**, the filament **54** includes a first portion **90** and a second portion **92**. Due to the focusing effects of the cathode cup **70**, the x-rays emitted by the first portion **90** predominantly strike the primary portion **80** of the target; while the x-rays emitted by the second portion **92** predominantly strike the secondary portion **82** of the target. The first portion **90** of the filament emits a higher current than the second portion **92**. It will be appreciated that although the first filament portion **90** is shown as being axially aligned with the primary target portion **80**, and the secondary filament portion **92** aligned with secondary target portion **82**, in cathodes which include inversion-type electronics, where the upper half of the filament is imaged on the lower half of the target, the relative positions of portions **90** and **92** are reversed.

The larger current of the first portion **90** is readily achieved by providing a larger coil diameter $\mathbf{d_1}$ for the first portion **90** than the coil diameter $\mathbf{d_2}$ of the second portion **92**. Other known methods of providing a larger current are also contemplated. The x-ray flux emitted (photons per unit area) is thus lower for the secondary target portion **82** than for the primary target portion **80**. To accommodate for any variations in the flux, the reconstruction processor **32** of the CT scanner (FIG. 1) is

optionally programmed to take the variations in flux into account when reconstructing the image.

Preferably, the electron source is configured to deliver the same (or at least substantially the same) specific load to the anode in all portions of the target. Preferably, the specific load on the first annular portion is within ± 10% of the specific load on the second annular portion. Specific load can be defined as the current (in mA) per unit area (cm^2) of the sloped surface.

The shaping of the filament exploits the shaping of the anode by distribution the current load over its surface appropriately. When the filament current is increased, the cathode emission will increase proportionately at all points, and the image of the filament upon the anode will become uniformly brighter, with substantially unchanged ratio of the currents in its first and second portions **90** and **92**.

In an alternative embodiment, the source of electrons **54** comprises two filaments of helically wrapped wire or conductive film, a first filament, similar in dimensions to the first filament portion **90**, emitting a first stream of electrons which are accelerated to strike the primary target portion **80**, the second filament, similar in dimensions to the second filament portion **92**, emitting a second stream of electrons which are accelerated to strike the secondary target portion **82**. The optimal relative heights of the target portions **80, 82** depends, in part on the CT scanner in which the x-ray tube is employed and in part on the desired coverage. For example, a multislice CT scanner using 100 slices will generally benefit from a larger $\mathbf{h_1/h_2}$ ratio than a 50 slice scanner of given width.

As shown in **FIGURE 3**, portions **96, 98** of the anode surface adjacent the target area **56** are also sloped, relative to the beam direction. The slope of these portions may be the same as that of the adjacent portion **80** or **82** of the target, or the slope may be different.

The configuration of **FIGURES 2 and 3** helps to alleviate the heel effect by providing a region **82** of greater

slope at the periphery of the primary portion **80**. Other embodiments which also provide for regions of different slope are shown in **FIGURES 4-6**, where similar elements are given the same numerals and different elements are given new numerals. The x-ray tubes and anode configurations for these embodiments are the same as for that of **FIGURES 2** and **3**, except as otherwise noted. It will be appreciated that in all the FIGURES, the angles α and β have been shown larger than they are in practice for clarity and ease of illustration.

In the embodiment shown in **FIGURE 4**, the primary target portion **80** is connected with the secondary portion **82** by a smooth or curved transition portion **110**, which is tangential to the angle α adjacent the primary portion **80** and is tangential to the angle β adjacent the secondary portion **82**. The curved portion **110** thus provides a gradual increase in the angle of the target slope from α, adjacent the primary portion **80**, to β, adjacent the secondary portion **82**. The angles α and β can have the same values as described for the embodiment of **FIGURES 2** and 3(e.g., 7° and 10°, respectively). In one embodiment, the curved portion **110** is about 1-2 mm in height h_3, i.e., only a small proportion of the target height h_T. For this embodiment, where the first and second portions are spaced by the transition portion **110**, $h_1 + h_2 + h_3 = h_T = w$.

It will be appreciated that although the transition portion **110** is shown as being of similar length in primary and secondary to portions **80** and **82**, in practice, where the angles α and β are closer to the 7° and 10° discussed above, the curved portion preferably has a height h_3 which is shorter than height h_1 of the primary portion **80** and is optionally shorter than the height h_2 of the secondary portion **82**.

The coil **54** preferably transitions smoothly to match the transition portion **110** of the target **56**. As shown in **FIGURE 4**, the filament coil **54** has a width (diameter) **d** which is inversely proportional to tan θ (d=K/tan θ), where **θ**

is the angle of the target at the point at which the electrons strike and **K** is a constant. Thus, for the first portion **90** of the coil, which corresponds to the primary target portion **80**, the width $d_1 = K/\tan\alpha$ and for the secondary portion **92**, the width $d_2 = K/\tan\beta$, as for the first embodiment. For a transition region **114** of the coil between the first and second portions **90, 92**, the width gradually changes, as a function of the tangent, tan **θ**. As for the first embodiment, the reconstruction processor **32** is programmed to accommodate for the change in flux which occurs as a result of the changing width of the filament coil **54**.

An advantage of this embodiment is that the placement of the image of the filament on the anode need not be as precise as for the embodiment of **FIGURES 2** and **3**, to avoid variations in x-ray output. As x-ray tube bearings wear, the anode tends to suffer increasingly from anode wobble. Having the gradually curving transition portion **110** rather than a sharp change between the primary and secondary portions **80** and **82** reduces the effects of the anode wobble upon x-ray output, prolonging the useful life of the x-ray tube.

With reference now to **FIGURE 5**, another embodiment of an anode is shown. In this embodiment, the target **56** includes a first portion **80** having the slope **α**, as discussed above (e.g., 7°). A second portion **120** is curved with the curvature increasing, away from the first portion **80**. In one embodiment, the second portion transitions from the angle **α** at the intersection with the first portion and increases to the angle **β** at its outer edge. **β** can be greater than 10°, for example, 12° or as high as about 15°. The optimal value of **β** depends, to some extent, on the number of slices used by the CT scanner. For larger numbers of slices a larger angle **β** is generally preferred. For example, for 50 slices, a **β** of 12° may be optimal, whereas for 100 slices, closer to 15° may be optimal for **β**.

As with the other embodiments, the filament **54** is preferably shaped to match the change in slope of the target, with the width being generally described by $d=K/\tan\theta$.

As with the embodiment of FIGURE 5, this embodiment is less sensitive to anode wobble than that of **FIGURES 3** and **4**.

FIGURE 6 illustrates an embodiment in which the flatter and more sloped regions are reversed in position. The target **56** slopes at an angle **α** near the inside or top of the anode and progresses smoothly to an angle **β** at the other end of the target area. In the illustrated embodiment, the cathode cup **70** is configured such that the filament **54** focuses a mirror image on the target. The filament **54** again produces electrons in inverse proportion to the slope of the receiving face. Because the embodiment of **FIGURE 6** is becoming progressively steeper, the path length through the anode traveled by x-rays which are generated below the surface of the anode becomes progressively shorter reducing attenuation and heeling effect. Although shown as a continuous smooth curve, it is to be appreciated that the target area can be two linear segments, two linear segments connected by a smooth transition region, a single linear segment and a continuously curved transition region and secondary region, or the like. As another option, a dual filament can be provided such that the target area can be expanded from the illustrated region **56** where the slope is between angles **α** and **β**, e.g. between 7 and 12°, and extended to a region where the slope is larger, e.g., 15°.

The invention has been described with reference to the preferred embodiment. Modifications and alterations will occur to others upon a reading and understanding of the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.